Edge sensors for segment control for large space telescopes

J. Scott Knight
Laura Coyle
Scott Acton

Ball Aerospace

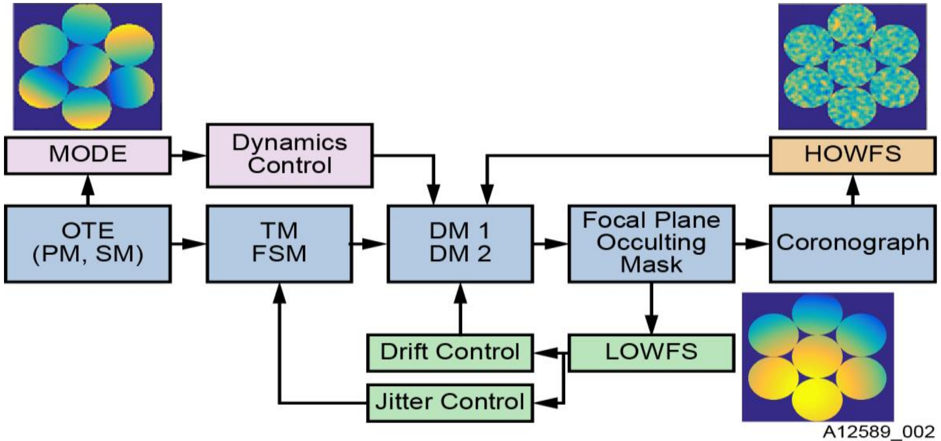
A large primary aperture enables both high sensitivity and fine spatial resolution

- If larger than practical for a monolith it requires segmentation
- If larger than launch vehicle fairing it requires deployment or assembly
- The full benefits of large size also require stability, precise alignment, precise pointing control
- These issues were resolved for JWST operating in IR. UV-optical solutions may need different approaches, or at least higher precision performance.
- High-contrast Imaging will drive many of the requirements.

Telescope Stability

Telescope Stability is one of the driving requirements for coronagraphy and diffraction limited performance at 500 nm.

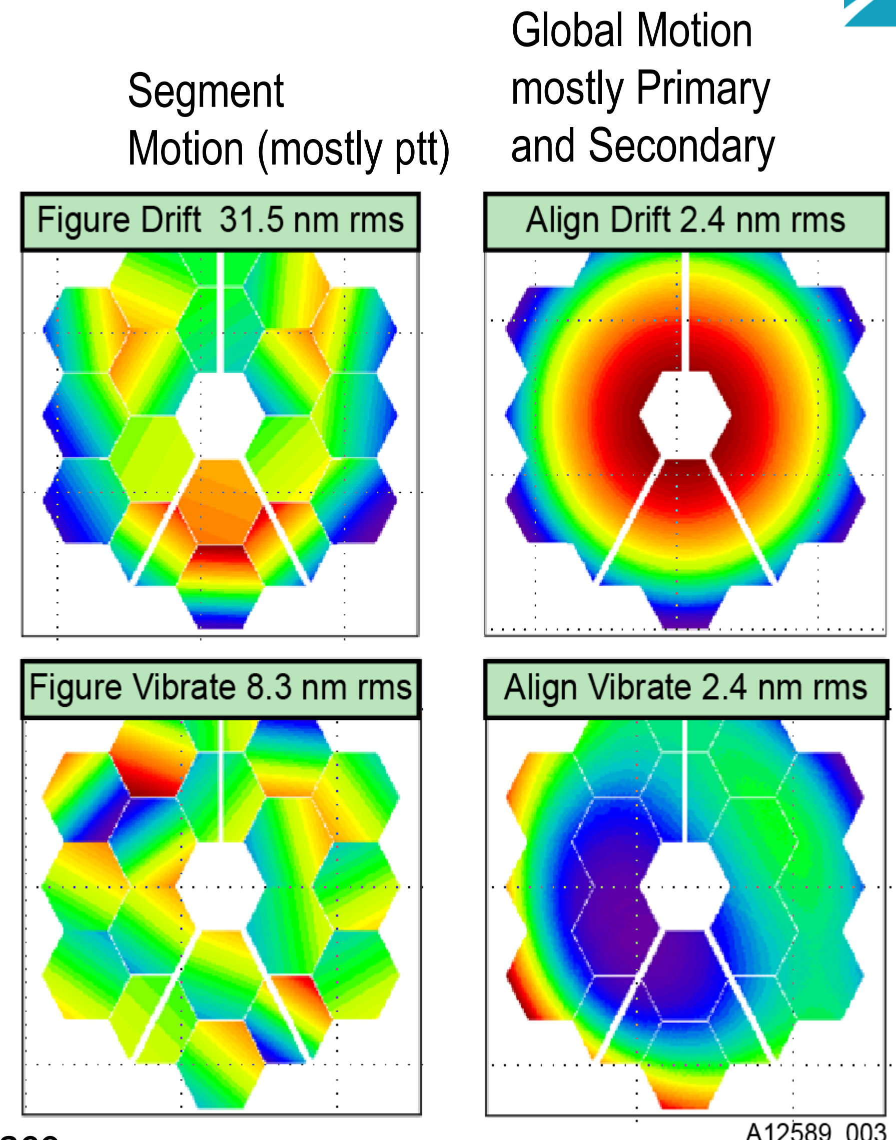
- Coronagraph Stability Goal is 10 pm/per coronagraph update (Stahl, Shaklan, etc.)
  - there needs to be more development in defining needs of 10 pm/time steps to assess further. Mostly on what the 10 pm part means.
  - Temporal peak-to valley vs. rms
  - wavefront vs surface
  - Spatial content
- Caveat is that exact stability levels are dependent on coronagraph design.
- But early assessments (Stahl) indicate segment level piston, tip, tilt stability is critical
- Will likely have WFIRST like LOWFS for at least drift control and LOS control
  - Relies on photons and bandwidth is limited by target star
- Will need more control at higher spatial bandwidths. i.e. Mid-order sensing and correction (MOWFS)



Example MOWFS implemented as MODE (a Distributed Control Concept)

JWST modeled dynamic performance

- For example, JWST dynamic performance is ~10 nm rms and due primarily to reaction wheels imbalance exciting structural modes, dominated by primary mirror modes
  - Alignment vibration is also a factor but smaller contributor
- Several factors make this worse including reduced damping at cryo
- There are several options to improve this performance
  - Will probably need architecture improvements in several areas
- One concept is to borrow from ground telescopes and use edge sensors to stabilize the segmented Primary Mirror

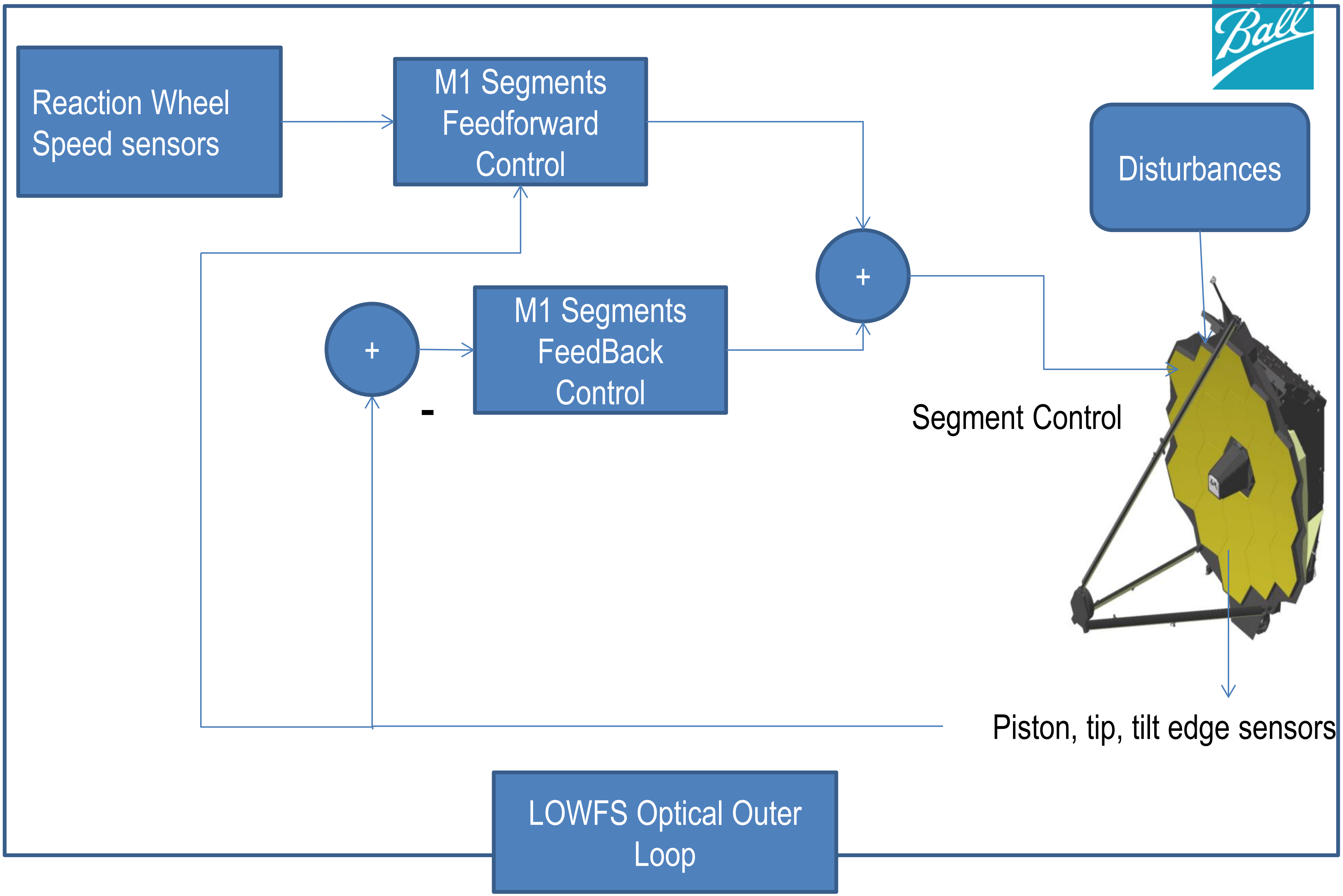


Now we want to go to picometer stability in space

Edge Sensors for segment alignment maintenance

- Ground telescopes have been using edge sensors to maintain alignment for generations of telescopes
  - Keck, SALT, TMT, GMT .....
- Generally these telescopes have requirements to maintain segment phasing at the nanometer class in the prescience of large disturbances
  - Gravity loading
  - Ground vibration
  - Air turbulence
  - Etc.

Local Segment Control Concept



Edge Sensing Pros and Cons

- Space is much more benign environment for sensing
  - Expect disturbances < 10 nm instead of 100's of microns
  - Operate in vacuum instead of air
  - Assume thermal stability maintained to < 10 mK
  - No earthquakes
  - No need to remove segments for maintenance
  - Assume thermal drifts are small and slowly varying compared to coronagraph time scales
- Dynamic control of space disturbances are generally from discrete known sources like reaction wheels during observations or slowly varying things like fuel slosh
- But, picometer sensing and control is at the edge of technology

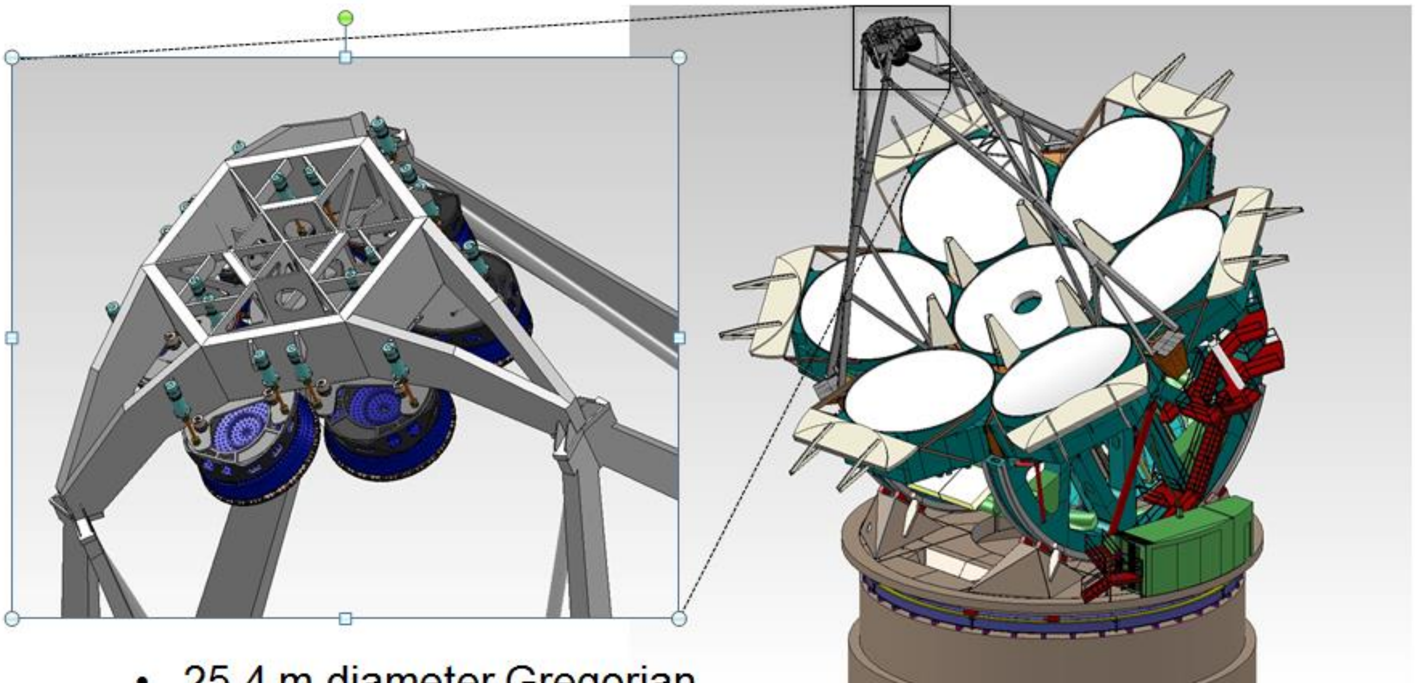
Approach for Large Space telescopes is to first look at the sensing noise.

GMT efforts are a starting point

GMT examined edge sensors for M2 Mirror

The Giant Magellan Telescope

GMT



- 25.4 m diameter Gregorian
- 7 x 8.4 m diameter M1 segments
- 7 x 1.1 m diameter M2 segments
- AO correction built into telescope with adaptive M2 (ASM)

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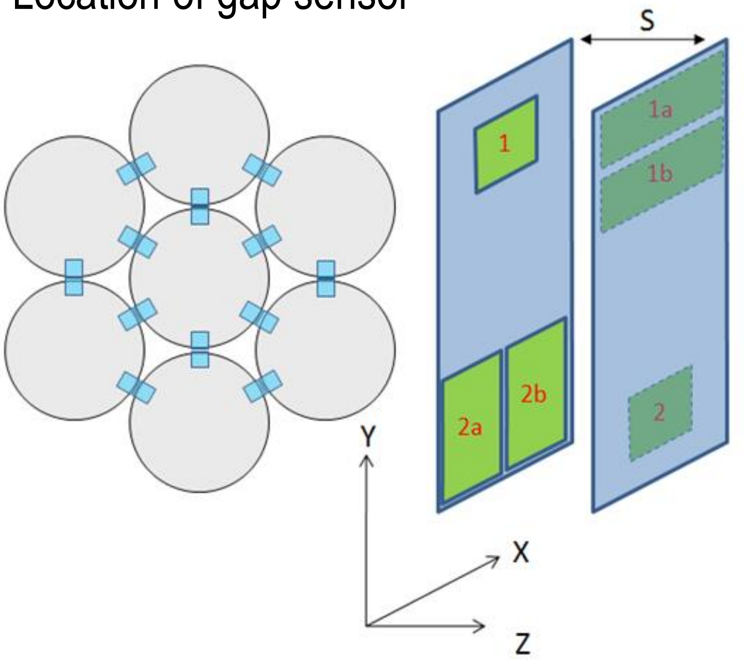
Note: M1 and final M2 system use optical edge sensing

GMT Early Concept M2 Edge Sensors

C=εArea/gap

Location of gap sensor



Constraints

- Remain in shadow of M2 support frame
- Precision of nanometers
- Long-term stability to relative tilt of >12 hr

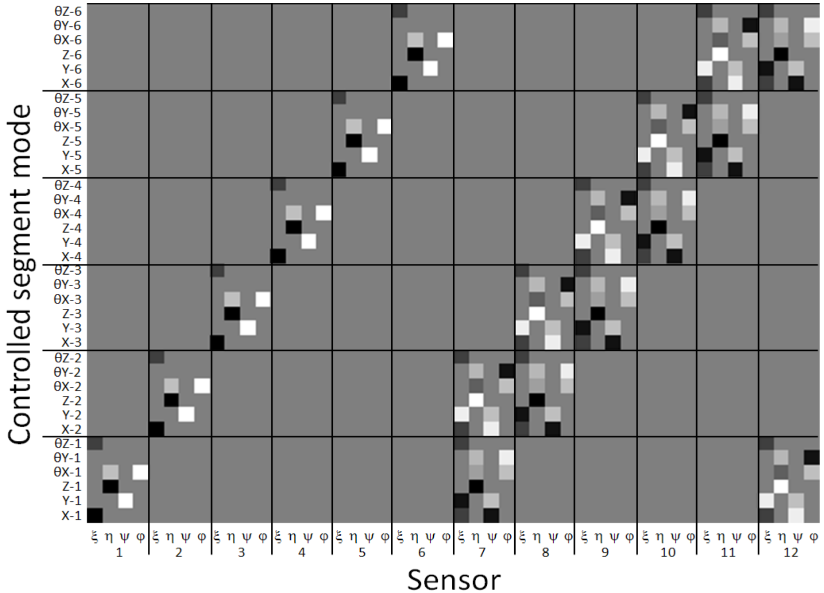
Design

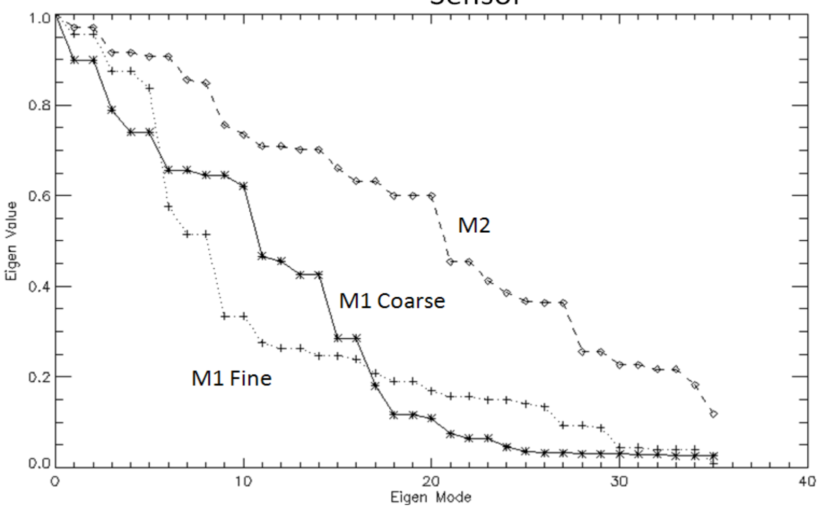
- Differential edge-mounted capacitive sensors
- Each plate made of Zerodur, bolted to edge of reference bodies
- Shielded as much practical
- One sensor per segment interface, 4 DOF sensitivity
- Small plate is 25 x 25 mm, 5 mm gap
- 50 Hz Bandwidth

	Queensgate	Physik-Instrumente	Micro-Epsilon	Our sensor
Model	NXD	D-100.00	CS-05	
Area	282 mm^2	113.1 mm^2	125	625 mm^2
Spacing	1.25 mm	0.3 mm	5.0 mm	5 mm
Noise at 50 Hz	1.3 nm rms	0.2 nm rms (est.)	0.6 nm rms (est.)	

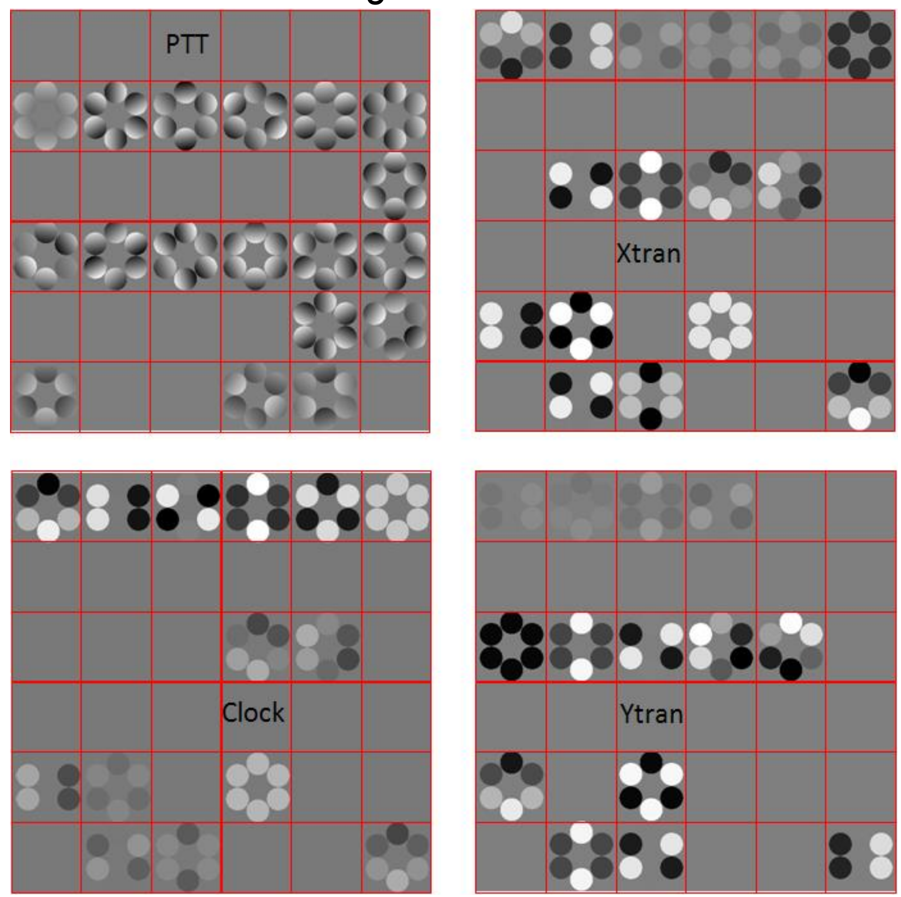
M2 Metrology: Eigenmode Analysis

Exact nature of global reconstructor depends on the sensor arrangement and segment arrangement





Eigenmodes



These edge sensors can sense most of the modes
Can't sense global clocking or tilt or segment figure changes

GMT Monte Carlo simulations

- Generated random sensor values, zero mean, scaled to match assumed sensitivity.
- Assumed sensitivities:
  - M1 Coarse: 2 microns (long-term stability)
  - M1 Fine: 1 nm
  - M2: ΔX, ΔY: 0.85 nm, ΔZ: 0.6 nm, θX: 12 nRad
- Used reconstructor to generate segment poses
- 1000 realizations

Simulation results (rms surface error)

	M1		M2
Mode	Coarse	Fine	
X translation	4.1 µm	0.7 nm	0.4 nm
Y translation	3.2 µm	0.6 nm	0.5 nm
Piston	4.1 µm	2.3 nm	5.9 nm
Theta-X	1.0 µRad	0.6 nRad	11.1 nRad
Theta-Y	1.4 µRad	0.5 nRad	9.5 nRad
Theta-Z	0.9 µRad	0.6 nRad	0.2 nRad

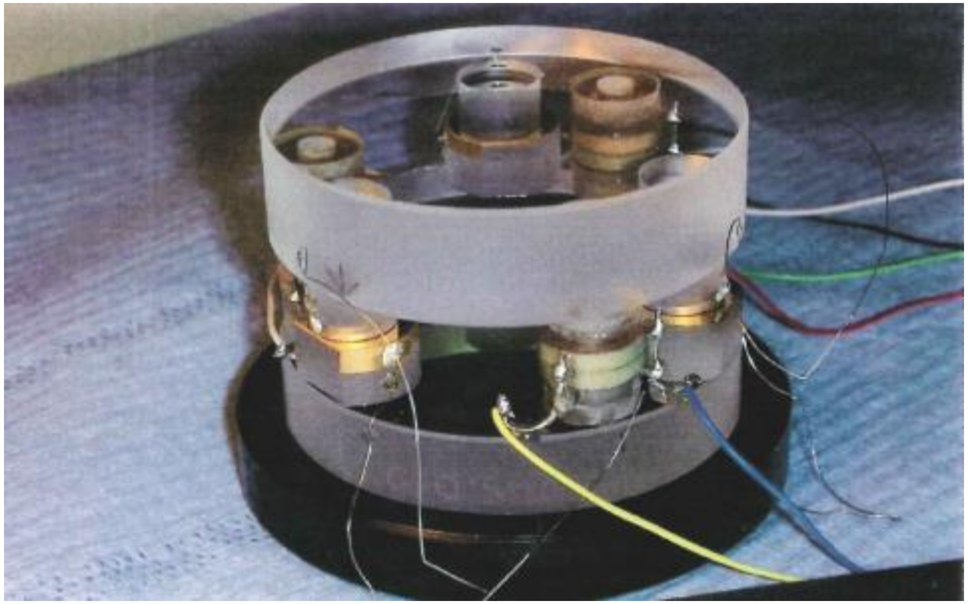
This met the GMT needs but is 3 orders of magnitude worse than where we want to be.

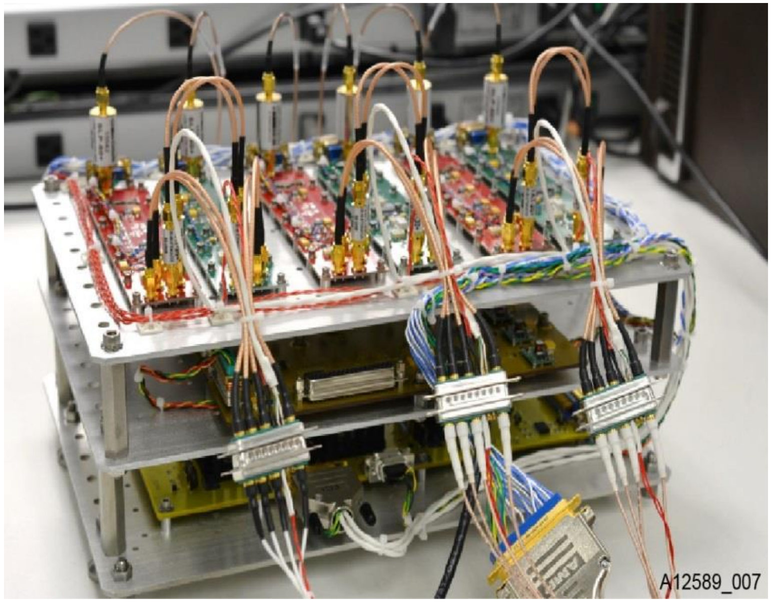
We need to improve sensor noise for space telescopes

Ball Custom Capacitance Sensor

This sensor was developed for use for gap sensing in an etalon for a tunable filter for a LIDAR instrument

- 3 Sensors and 3 PZT stacks to control piston tip and tilt of etalon in the presence of dynamic disturbance
- Etalon control reqt was 16 pm

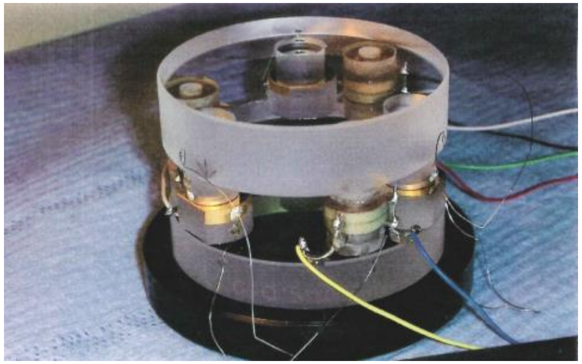




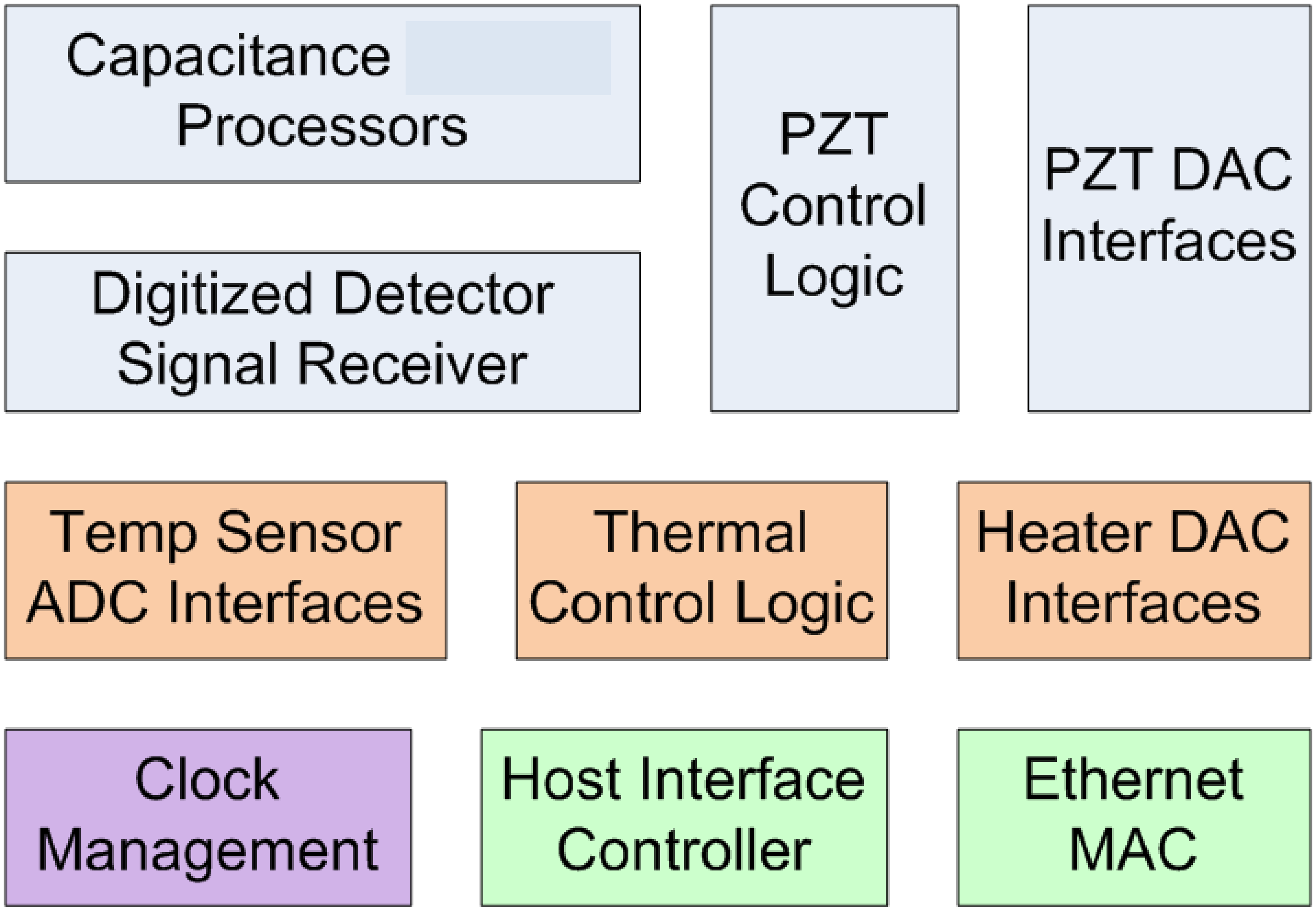
Brassboard

Key Requirements (Etalon Control System)

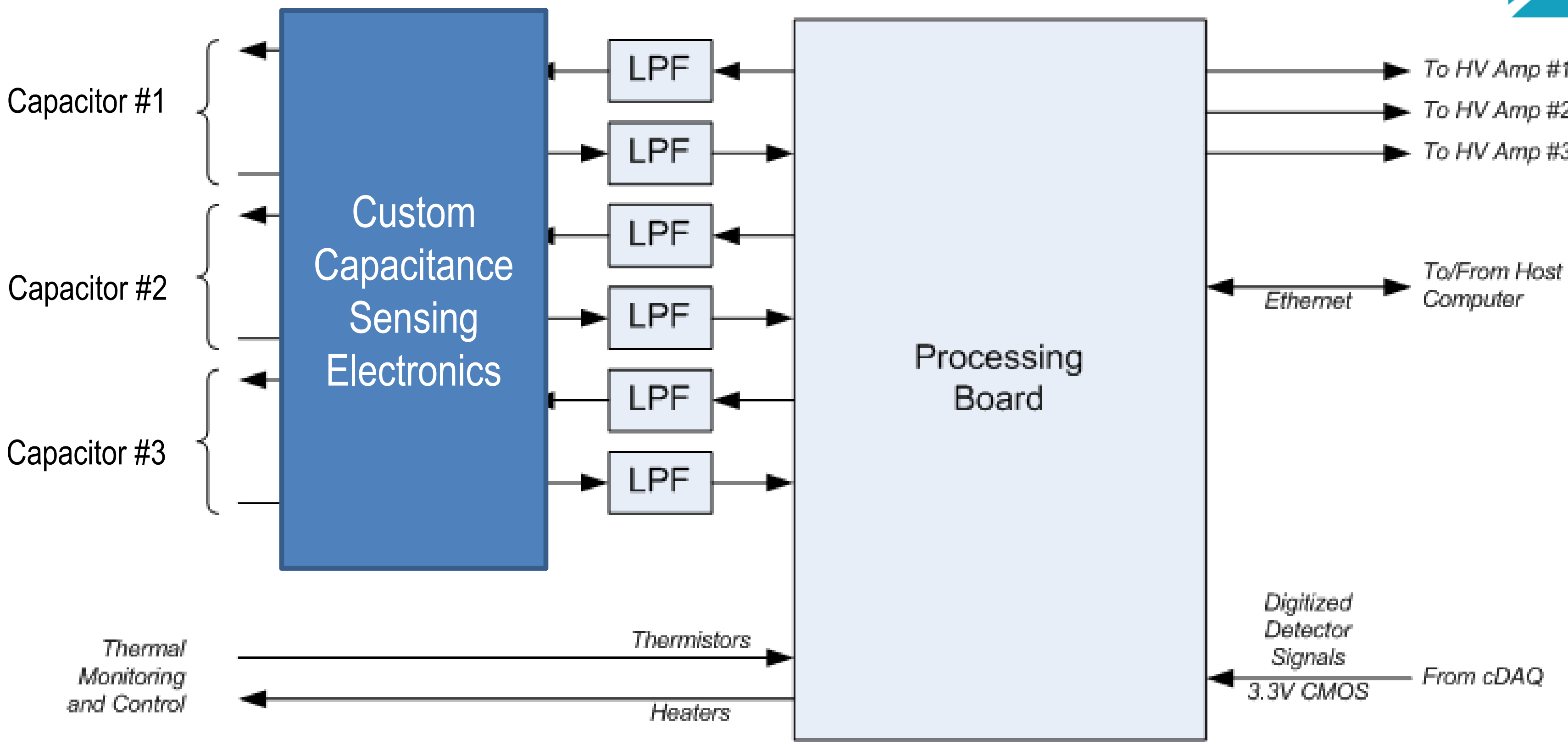
- Provide drive to three PZT actuators
  - "Low" noise
  - To maintain etalon gap
- Implement control system processing
- Implement Thermal control
  - Monitor temperatures of capacitors
  - Monitor etalon housing temperature
  - Drive etalon heaters
  - Control etalon housing temperature
- Have path to spaceflight

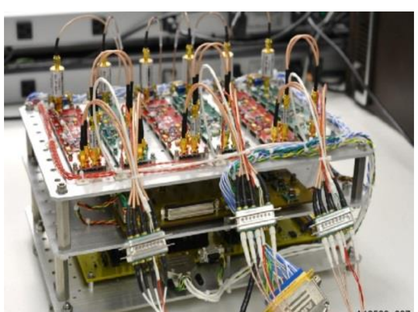


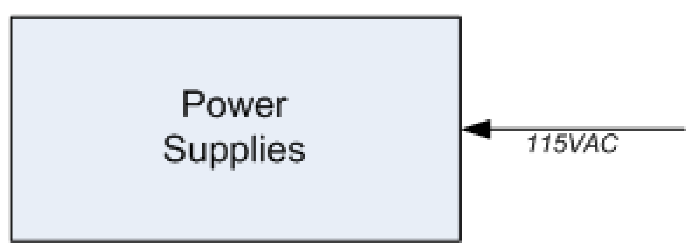
Processing FPGA Architecture



Demonstration Processing Box





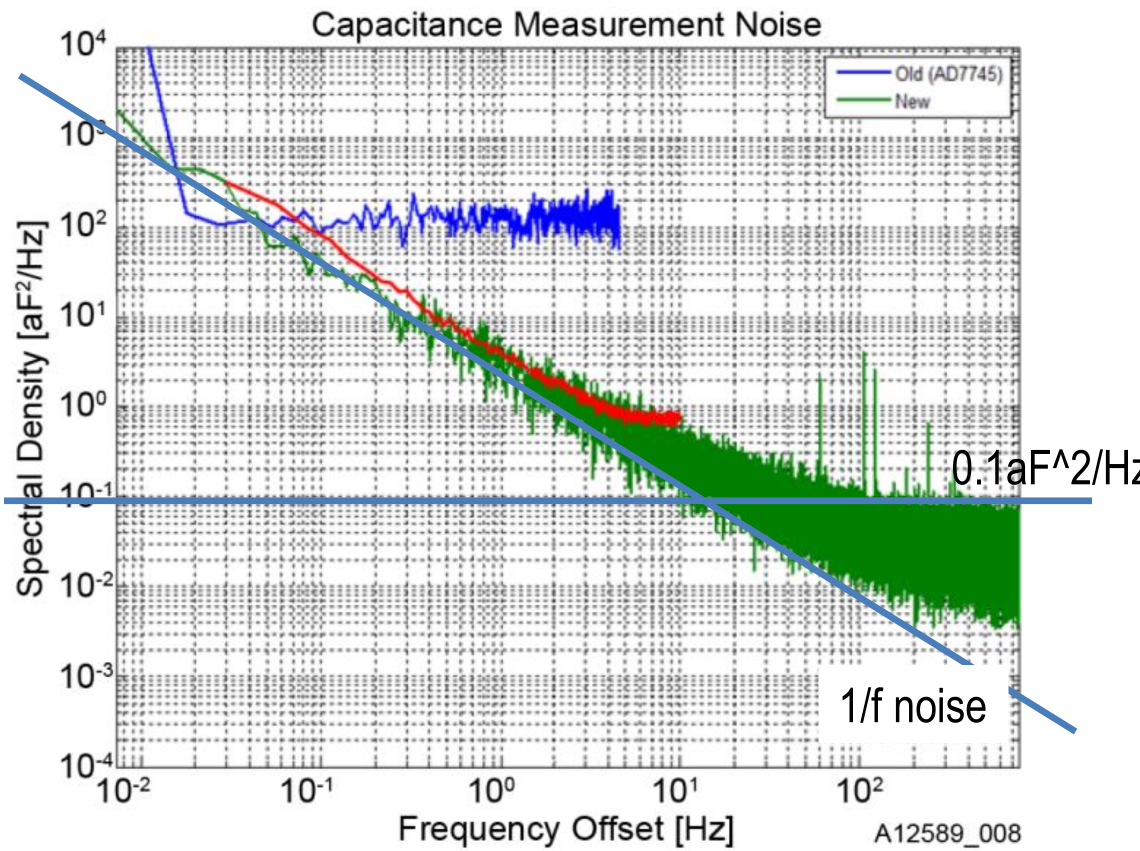


Capacitance Sensing

- Limiting factor for etalon control system performance.
- Must make very low-noise capacitance measurements of three sensors.
- Must have very low cross-talk between sensors

Capacitance Sensing

- Comparison of performance of custom approach vs. that of the a typical instrumentation amplifier.
- Custom approach has lower overall noise floor - and does not suffer crosstalk issues
- Similar 1/f performance to instrumentation amplifier
  - Much of 1/f noise is removed by standard techniques with processing and other architecture elements
  - But there remains some residual 1/f noise that dominates the open-loop sensing (see next page)



Open-loop Gap Measurement Performance

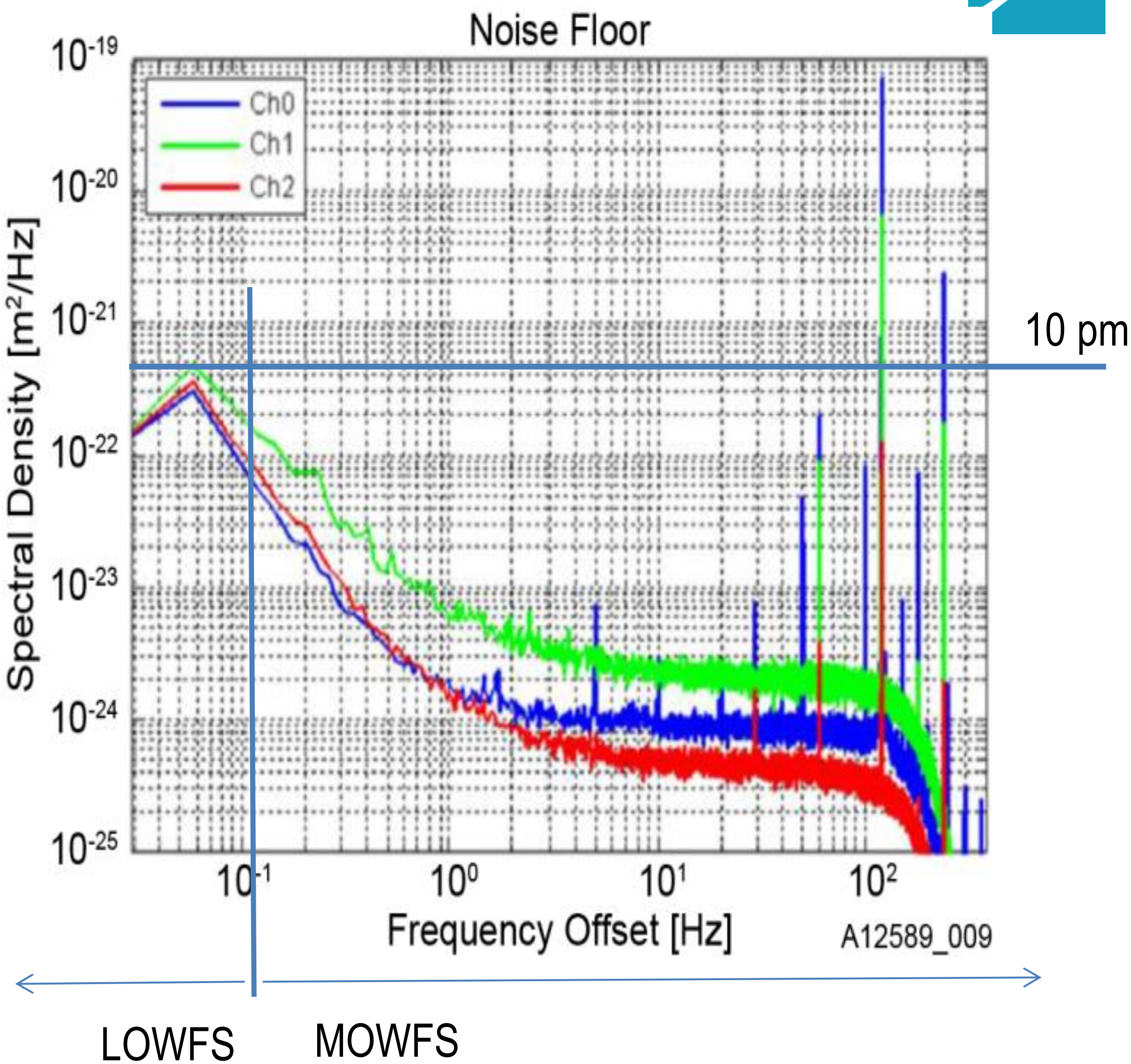
- Open loop power spectral density of the three capacitive sensors is calculated to demonstrate the noise in the gap measurement versus frequency. The average integrated noise from 0 to 60 Hz is 10 pm RMS with a dynamic range of 100 dB

- Effect of control loop was predicted but not measured. Program concluded before confirming optical measurements were made.

Performance improvements are possible for segment control

- Possible design tweaks to electronics for 1/f low frequency performance and could extend Control BW to 200Hz at same noise floor

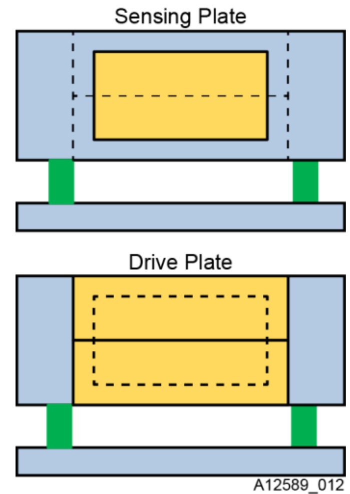
- Performance could also be improved by Optical Outer Loop LOWFS sensing & correction of sub Hz noise



First-order Sizing Assessment for a Space Telescope

Space Mission based on Custom Capacitance Measurement

		epsilon	8.85E+00	pF/m
		Area	4000	mm^2
		distance	0.25	mm
		accuracy	0.005	nm rms
		bandwidth	60	Hz
C=epsilon*A/d		capacitance	141.664	pF
		delta capacitance	2.833E-06	pF
			2.833	aFarad
		PSD Need	1.338E-01	aFarad^2/Hz



- Tradeoff between Area, Gap and Bandwidth
  - 200mm x 40mm Plates is OK
  - 0.25 mm gap is marginal
  - Needs further mechanical development but to first order edge sensing concept appears feasible.

- Possible Future Efforts
  - Need to make measurements with this geometry
  - Needs control loop simulation and study
  - Control and sensing residual by higher order global spatial terms and segment level figure
  - Examine other sensor configurations/types (inductive /optical)